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TITLE. GETTING LUNAR ILMENITE: FROM SOILS OR ROCKS?

AUTHOR(S) D. T. Vaniman, Los Alamos National Laboratory,
EES-1, MS D462, Los Alamos, NM 87545
G. H. Heiken, Los Alamos National Laboratory,
EES-1, MS D462, Los Alamos, NM 87545

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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Getting Lunar Ilmenite: From Soils or Rocks?

D. T. Vaniman¹ and G. H. Heiken¹

Abstract

Lunar soils or rocks can be mined as sources of ilmenite for producing oxygen. However, separable crystals of loose ilmenite in lunar soils are rare (<2%) and small (<200 μm); most ilmenite in the regolith is locked together with silicate minerals as rock fragments. Since fragmentation of rock sources must be attempted to win appreciable amounts of ilmenite (~10% or more), selective collection of high-Ti basalt fragments larger than 1 cm for fragmentation and ilmenite beneficiation may be advantageous over extensive processing of fine lunar soil. Many alternative processing schemes for fragmenting rocks on the Moon have been proposed; one process which was tested early in the Apollo program successfully disaggregated lunar and terrestrial basalts by passive exposure to low-pressure alkali (K) vapor. This process is worthy of reinvestigation.

Introduction

Lunar ilmenite is a potential ore for production of oxygen (to be used in propellants and for life support), with byproducts of iron and refractory TiO_2 . Schemes for ilmenite processing to make oxygen rely on reductants, and several different processing schemes have been considered (e.g., reduction by CO - Cutler and Krag, 1985; and reduction by H₂ - Williams, 1985). Although the requirements for purity of ilmenite feedstock are still poorly constrained, a feedstock of ~90% pure ilmenite is suggested by Cutler and Krag, and Williams has experimented with 93% pure ilmenite. Electromagnetic concentration is generally envisaged as the method of choice for obtaining these ilmenite rich feedstocks (Agosto, 1985). Lunar

¹Earth and Environmental Sciences, MS D462, Los Alamos National Laboratory, Los Alamos, NM, 87545

soil (the <1 cm fraction of the regolith) is commonly assumed to be the source of the ilmenite ore because the fine-grained soil contains loose single crystals of ilmenite which may be collected without crushing hard rocks.

Collection of mare soils for processing is one of the simplest conceivable lunar operations. Lunar mare plains cover 6.4×10^6 km² of the lunar surface; within this area, there are approximately 1.2×10^6 km² of mare regolith overlying high-Ti basalts. All of the regolith is readily accessible. The fine-grained soils of the regolith are also sinks for dispersed surface-correlated volatile elements (hydrogen, carbon, nitrogen, and helium) that have potential applications in life support or (for ³He) export to Earth for energy production. A special subclass of mare soils, the pyroclastic deposits, contain a broad variety of surface-coating volatile elements (Zn, Na, K, Cl, as well as S) that have potential uses but as yet no well-defined applications. Soils are indispensable for the collection and use of these volatile components. However, there are several problems in the collection of ilmenite grains from the fine-grained soil fraction of the mare regolith.

The assumption that relatively pure (e.g., 90% purity) ilmenite concentrates may be simply collected from lunar soil is confronted by several problems. Most ilmenite fragments in the soil are not clean, discrete crystals; instead, most are microlithic fragments with adhering silicate minerals. To extract the ilmenite that does occur as single crystals while avoiding most (but not all) of the microlithic fragments, one must sieve to sizes finer than about 100 μ m - a daunting prospect for large-scale operations in soils with high electrostatic charge and without benefit of wet-sieving. Even if this were possible, the ilmenite abundances extractable as single crystals are very small (about 2%). Additionally, it is the fine soil fraction in which the original rock and mineral constituents excavated from the bedrock have been most altered, both by high-energy charged particle or solar wind bombardment and by meteoroid impact. The omnipresent agglutinates, which are vesicular and slaggy particles of fused soil, have a grain size generally <1 mm and therefore occur almost entirely within the fine soil. Agglutinates may present problems in the extraction and beneficiation of ilmenite from soil, because they will require precise magnetic separation techniques. It may be far better to face the problem of crushing or disaggregating the rocks with high ilmenite content, rather than deal with the dispersed and very fine grained ilmenite component of the regolith.

But exposures of mare bedrock are very rare. The only observed outcrops of mare basalt were those seen in the steep walls of Hadley

Rille at the Apollo 15 site, in a location so inaccessible that they could not be sampled. If large quantities of rock are to be sought for ilmenite extraction, it would be most practical to collect the relatively coarse basalt pieces and boulders that are generally concentrated around the gently sloping rims of craters ~10m and larger in diameter. Around craters of ~100m and greater diameter these boulders may be so large that they become obstacles, and optimum operations will have to consider abundances of rock versus soil as well as the accessibility of mining sites.

It is important to consider (1) how coarse the size range of particles collected must be to avoid the collection of agglutinates, and (2) how other coarse samples (principally regolith breccias) can be identified and rejected. Although agglutinates larger than 1 mm do occur, they differ from their smaller siblings by occurring mainly as splash coats on other soil materials, and by their low vesicularity and tendency to be devitrified (Heiken, 1975). Extensive agglutinate-like splash coats, however, tend to be more typical of highland than of mare areas. Heiken (1975) found that a typical Apollo 17 mare soil (71061) contains no agglutinate glass coarser than 1 mm; all constituents in this soil coarser than 1 mm are basaltic rock fragments. In this particular bulk soil, the coarse (1 to 10 mm) mare lithic fragments accounted for 23% of the total soil weight. It is likely that a high-Ti mare soil (without highland massif mixing) will, if sieved to collect the >1 mm fraction, consist mostly of basaltic rock fragments and regolith breccias; if sieved to collect the >1 cm fraction, it is almost certain that the collection will consist only of basalts and regolith breccias.

Based on the sample data from the Apollo 11 site, all fragments over 50 g are either basalts or regolith breccias (Fruland, 1983). Of these samples, about 40% are basalts and 60% are regolith breccias. If the problems of small ilmenite size and low ilmenite abundance are to be avoided, then the basalt collection system must be intelligent enough to reject the regolith breccias. Regolith breccias can be readily distinguished from basalts on the basis of density (the densest Apollo 11 regolith breccia is $<2.6 \text{ g/cm}^3$, compared to $3.3\text{-}3.4 \text{ g/cm}^3$ for basalt) and on hardness. These properties can be evaluated by physical, electrical, or acoustic methods while the mining equipment is gathering the feedstock. An intelligent mining machine could not only provide a pure basalt feedstock, but also provide a wealth of detailed data on lunar geology.

Boulders in Lunar Soil

Ilmenite abundances in high-Ti mare basalts range from 10 to 20%; careful exploration and site selection may provide basalt fragments of sufficiently large grain size that fragmentation to 0.25 mm can lead to ~10% extractable ilmenite of acceptable purity (Heiken and Vaniman, in press). It is important to emphasize that the major effort involved will be in crushing the >1 cm "boulders"; these can be collected from the surface of the regolith, without excavation.

How many >1 cm basalt fragments are available from a typical mare regolith? The only visual measurements of such coarse fragment abundances were made from closeup photographs in the Surveyor and early Apollo missions (Surveyor and Apollo 11 - Shoemaker et al., 1970a; Apollo 12 - Shoemaker et al., 1970b). These data are summarized in Figure 1. Some uncertainty is involved in the extrapolation to particles of multi-centimeter size; for example, the Apollo 12 photograph used was a closeup that covered an area of only 72 by 82 mm (Shoemaker et al., 1970b). Nevertheless, the power function curves in Figure 1 show relatively good agreement between the Apollo 11 and Apollo 12 photo measurements. (The Surveyor television pictures covered more area; Surveyors I, III, and VI are very close to the extrapolated Apollo estimates whereas Surveyor VII is considerably coarser and Surveyor V is more fine-grained - see Shoemaker et al., 1970a).

Using an average high-Ti basalt density of 3.35 and an assumption that 40% of the >1 cm fragments are basalt (with the remaining 60% regolith breccia), we have estimated the amount of >1 cm fragments necessary to obtain an arbitrary large mass of ilmenite for industrial-scale yearly oxygen production. This mass of ilmenite was chosen to be 10^4 MT, to match the mass needed to supply the model plant described by Cutler and Krag (1985) which would produce 10^3 MT of oxygen per year. Heiken and Vaniman (in press) suggest that ilmenite recovery of better than 10% is obtainable from crushed or disaggregated high-Ti mare basalts (in contrast to <2% from uncrushed high-Ti mare soils). Using an assumed value of 10% ilmenite from basalt, a total mass of 10^5 MT of basalt is needed for the crusher/disaggregator that will feed the model oxygen plant for one year.

The curves in Figure 1 can be used to estimate the surface area needed to provide enough >1 cm basalt fragments to produce this mass. The result is influenced by the shape of particle used in the calculation (we have assumed particles intermediate between spheres

and cubes); with such particles, the area that must be skimmed is approximately 75 km².

Another approach to this calculation is to examine the coarse sieved fractions from large regolith samples. Figure 2 represents the coarsest sieve data available (Apollo 14; LSPET, 1971). Although not collected from a high-Ti mare sample, the area shown for typical Apollo 14 soils in Figure 2 closely matches the cumulative particle number field for Apollo 11, Apollo 12, and three Surveyor sites shown in Figure 1 (when converted from mass to area). About 1% by weight of these typical soils consists of fragments larger than 1 cm. To feed the model oxygen production plant, about 150 km² of regolith must be sieved to 10 cm depth to obtain enough fragments of >1 cm basalt.

These two estimates differ by a factor of two. The major unconsidered factor in the second estimate (based on Figure 2) is the fact that the sieved soil analyzed did not account for the rare but significant basalt boulders (>10 cm) scattered across all mare regoliths. The largest boulder observed at the Apollo 11 site was about 0.8 m across. This boulder alone probably weighs more than 1 MT. It does not take many large fragments at the low end of the curve in Figure 1 (>10 cm) to considerably raise the mass of basalt collected.

Another factor needs to be considered in collecting basalt fragments: the possibility of selectively culling material from crater rims where coarse blocks are relatively more abundant than in the "bland" mare plains. The upper curve in Figure 2 represents regolith from the fresh debris along the rim of Cone Crater at the Apollo 14 site. The size distribution in this upper curve indicates that if such regoliths are processed for >1 cm particles and blocks, there may be an approximately 10-fold increase in the mass of material collected relative to the "bland" mare plains. This would lower our area estimate needed to feed the model oxygen plant for one year from 150 km² (using a mining depth of 10 cm and the lower curves in Figure 2) to 15 km² (using the same depth and the upper curves in Figure 2). Moreover, closeup photographs of the boulders on the rim of Camelot Crater at the Apollo 17 site show that most if not all are basalt. Without a significant regolith breccia component, the area to be mined can be further reduced to ~6 km².

Mining Crater Rims

Camelot Crater provides a specific example of a mineable crater rim. Camelot is a fresh crater, ~70-95 my old, and at 650 m diameter it is the largest crater visited by the Apollo 17 crew (Wolfe et

al., 1981). It is comparable in size to many of the craters in the "central cluster" (Figure 3), and Camelot is therefore not an anomalous feature.

The rim of Camelot is littered by particles of basalt ranging up to >3 m in diameter. Although the boulder field is discontinuous, the surface of the rim visited by the Apollo 17 astronauts was found to be ~30% covered by basalt boulders. This abundance of basalt boulders falls off markedly "within a few meters" from the rim; examination of photos and maps from the Apollo mission suggest that the width of the rim most littered with boulders is probably about 20 m. More boulders are found within the inner slopes of the crater rim, but possible problems of mobility and access could prevent use of the inner slopes of craters for mining. Within this 20 m band along the crater rim, if excavations of 1 m are made and if the basalt blocks also comprise ~30% of the cross-sectional area, one crater such as Camelot could provide over 10^4 MT of basalt. Ten such craters could feed the 10^3 MT O_2 model plant described above for one year.

The central cluster ejecta, south and east of Camelot Crater, is characterized by its coarse debris and an abundance of large boulders. Each of the 150 boulders marked in Figure 3 is a few meters in diameter and each has a probable mass in excess of 10 MT. Boulders of 1 MT mass are probably an order of magnitude more abundant in the central cluster. Since boulder masses scale upwards with the cube of the boulder diameter, such rich fields of large rocks could be attractive areas for mining.

The preference of basalt source, whether large areas of "bland" mare regolith with small boulders or smaller areas of crater rims and crater clusters with large boulders, would depend on the mobility versus the power of the mining equipment. In this regard, it is important to consider that a mare basalt boulder of 1 m^3 has a mass of about 3.3 MT. It may be preferable to construct mining equipment which will roam with a range of tens of kilometers and be intelligent enough to recognize and reject regolith breccias, than to build massive systems of limited range. A preference for collecting many smaller boulders may also be compelled by the relatively easier prospect of fragmenting cm-scale particles rather than m-scale boulders.

Processing Rocks: Fragmentation

A major concern in extracting ilmenite ore from rocks is the problem of crushing. Conventional terrestrial crushing mills operate in stages, taking material of multi cm size through jaw crushers,

cone or gyratory crushers, and grinding mills to produce fragments with a practical reduced size limit of ~ 0.25 mm (Vincent and Rickard, 1973). However, the absence of fluids (either liquid or gas) and other aspects of the lunar environment are likely to limit the use of such equipment (Podnieks and Roepke, 1987).

There are many alternative methods for fragmenting rock samples. Podnieks and Roepke (1987) and Lindroth and Podnieks (1987) summarize the possibilities of explosive, CO_2 laser, microwave, and solar fragmentation processes. All of these innovative processing schemes are promising. We wish to add to this list a process originally proposed as a natural mechanism of rock erosion on the Moon: rock fragmentation by alkali metal vapors (Naughton et al., 1971).

Naughton et al. (1971) completely disintegrated a sample of lunar basalt 12022, by exposing it to potassium vapor with a maximum pressure of 10^{-4} torr under mild thermal cycling (100°C) for a period of one lunar day (14 Earth days). Their study of basalt fragments subjected to this process indicated that disaggregation occurs by breaking apart at grain boundaries, due to the volume differences resulting from exchange of K for Na in the feldspar crystals. The experiments they performed were designed to test the possible natural operation of this process under simulated lunar daytime conditions, rather than to optimize the sample fragmentation rates. It is likely that differing conditions of K pressure and temperature or uses of alternative or mixed gases (K-Cs?) will result in more rapid and effective fragmentation. Although this process will require stocks of K for operation on the Moon, it is probable that more extreme heat processing of the silicate mineral tailings after ilmenite removal will allow recovery and reuse of the K. This appears to be a simple fragmentation process that could operate very well in the lunar environment.

Conclusions: Production of Oxygen from Rocks and Other Volatiles from Soil and Pyroclastic Deposits

We propose that high-Ti mare rocks are more attractive than high-Ti mare soil as a target for ilmenite separation. We make this proposal because (1) single ilmenite grains in the lunar regolith are small (generally < 0.2 mm), (2) even in high-Ti mare soils the single ilmenite grains are not abundant (2% or less by volume), and (3) most ilmenite in the regolith is locked together with silicate minerals in little "rocklets" that will require fragmentation anyway. Since processing which includes fragmentation seems inevitable it is important to consider the option of bypassing the

fine soils and processing instead the coarse and abundant ilmenite in >1 cm pieces of basalt from the regolith. However, we do not propose that the valuable commodities of the regolith (particularly volatiles) be ignored.

A lunar oxygen production plant is often pictured as being centralized, relatively large, and stationary. Such plants are generally visualized with fixed foundations, having earth movers that bring feedstocks to the plant and remove the tailings left after oxygen extraction. An alternative plant architecture may be one in which only the power source (probably nuclear) is in a fixed location, the oxygen production plant is movable but generally stationary, and dispersed rovers collect coarse-grained ilmenite basalts for the oxygen production plant. The oxygen production plant could be moved after its rovers deplete the readily collected boulders in its local area, but would remain stationary while in operation.

The rovers could fulfill several tasks in addition to supplying the oxygen production plant. With little additional mass, the rovers could be equipped with a small heating chamber and a gas collection system; regolith could be brought into the chamber for volatile extraction and collection (stepwise heating could be used to partially separate the gasses collected). While the rover moves, over constantly new terrain, it can also serve the function of a very slow but thorough robot geologist, scanning the variety of particles in front of it and selecting any unique samples (using optical imaging and x-ray analysis systems) for periodic collection and return to Earth. This cooperation between a relatively stationary, dumb oxygen plant and mobile, intelligent rovers could provide oxygen for space propulsion, ^3He for use on Earth, other gasses for use in space, and a very carefully collected sample suite for better understanding of the Moon.

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Figure 1: Cumulative number of particles, increasing with decreasing particle size, on the surfaces of typical lunar regoliths. Data are compiled from photos and television images. This figure is modified from those in Shoemaker et al. (1970a,b).

Figure 2: Illustration of the occurrence of more abundant coarse fragments in crater rim soils (the example is Cone Crater) than in the typical lunar regolith. The shaded region of typical soils is comparable to the shaded region in Figure 1. This figure is modified from LSPET (1971).

Figure 3: Locations of Camelot Crater and the central cluster ejecta field at the Apollo 17 landing site. The "x" symbols mark locations of large boulders that could be mapped from orbital photography; each of these boulders is large enough to have a mass in excess of 10 MT. This figure is modified from Muehlberger et al., 1973.

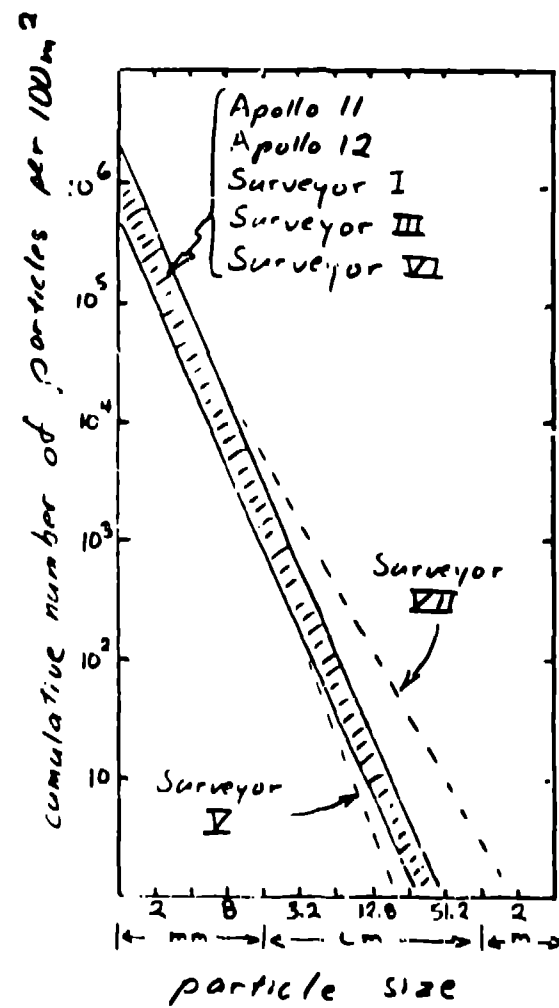


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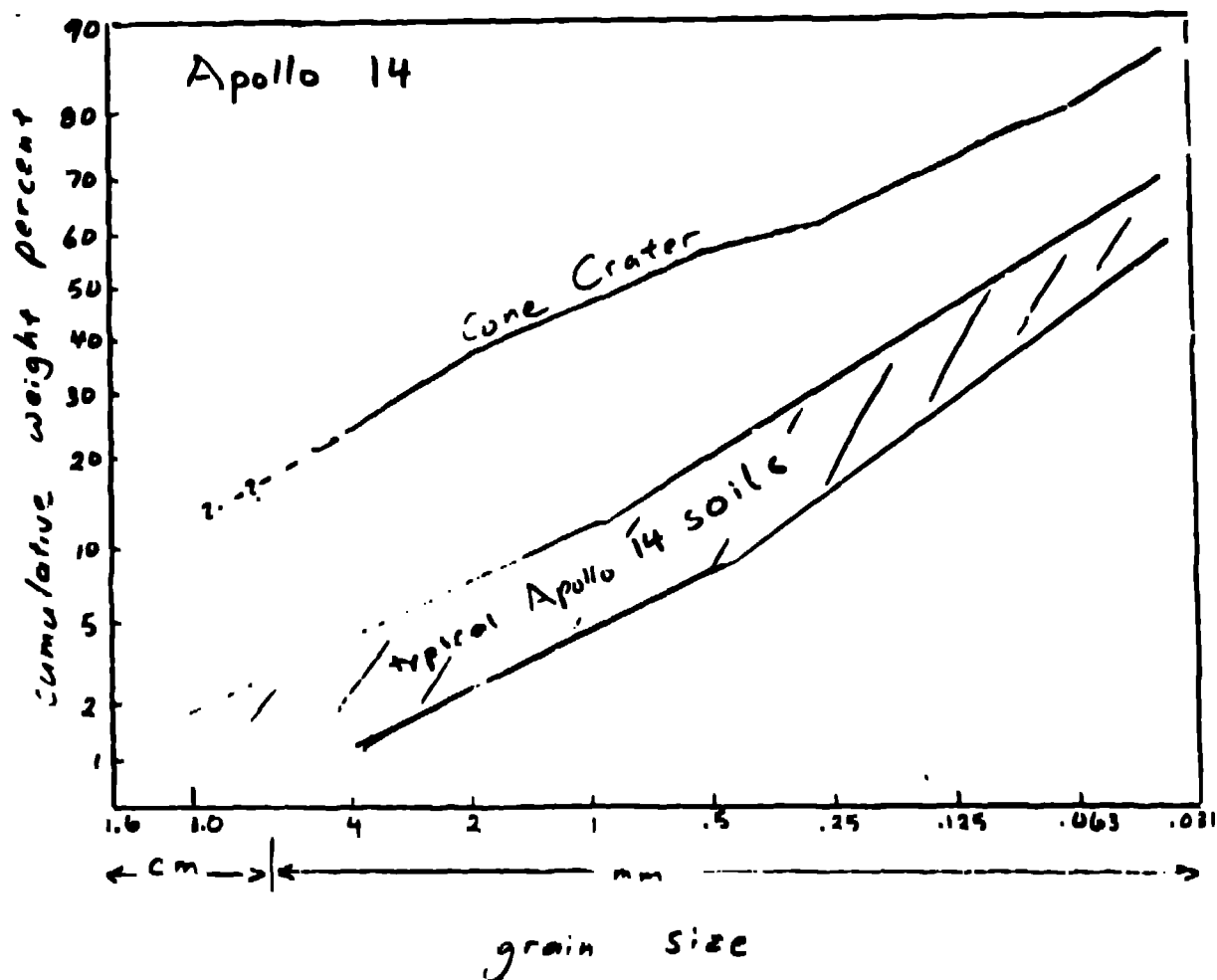


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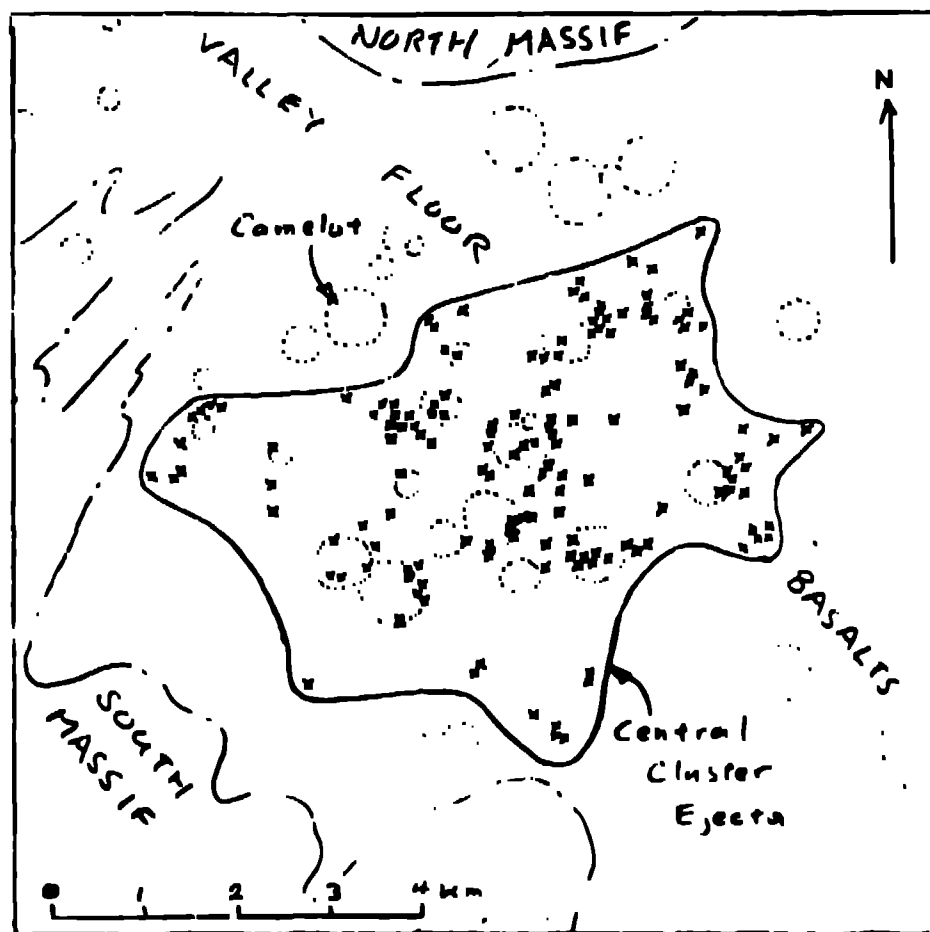


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